African Journal of Agricultural Research Vol. 3 (10), pp. 650-666, October 2008
Available online at http://www.academicjournals.org/AJAR
ISSN 1991-637X © 2008 Academic Journals

Full Length Research Paper

Combining multi-agent simulations and cost-benefit analysis to evaluate policy options for the management of livestock effluents in Réunion Island

Stefano Farolfi[1]* Louise Erasmus[†2] Christophe Le Page[3] and Pierre Bommel[3]

[1]CIRAD, UMR G-EAU and CEEPA, University of Pretoria, South Africa.
[2]CEEPA, University of Pretoria, South Africa.
[3]CIRAD, UPR GREEN, Montpellier, France.

Accepted 19 September, 2008

This study uses a multi-agent system to simulate the behaviour of economic players in a context of rapidly evolving environmental policy. The area under study is represented by a sector of a French overseas Department, Réunion Island, with a high concentration of pig farms in the upland region and extensive sugarcane plantations in the coastal zone. We first simulate local pig farmers' reactions to several policy options aimed at reducing the pollution coming from pig rearing. Multi-agent simulations are then coupled with cost-benefit analysis in order to calculate the net present value of different policy options. Advantages and limits of the use of the proposed methods to support decision-making are finally discussed.

Key words: Environmental policy, decision-making, livestock effluents, Réunion Island, multi-agent system, cost-benefit analysis.

INTRODUCTION

Nitrogen and phosphorous rich effluents from intensive livestock farms are generally considered good fertilisers, but can become a source of pollution for the soil, surface and ground water when they reach excessive concentrations. In areas of high-density livestock production, the persistent accumulation of elements such as nitrogen is a widespread problem.

In the European Union (EU), national and continental policies have been implemented to regulate the spreading of these effluents on farm land (in France: Ministerial Orders of 1992 modified in 1999, Code of Good Farming Practice, 1994; in the EU: Nitrates Directive n. 91/676/CE). Besides the specific legislation about livestock effluents, under the French law, pig farms are considered "environmentally sensitive installations" (cf. National Act on Environmentally Sensitive Installations -ICPE- of 1976 and subsequent modifications), and the recent National Water Act of 30 December 2006, which integrates the European Water Framework Directive (n.2000/60/CE), provided for a pollution charge to be levied by the catchment agencies on livestock producers on the basis of the polluter-pays principle. On the other side, the State, the local authorities and the catchment agencies can provide subsidies to partially or totally cover farmers' costs for the investments required to comply with the new environmental regulations.

Under the European Nitrates Directive and after a long negotiation with national farmers' organisations, France launched a system based on maximum spreading limits according to the vulnerability and current degree of pollution of land on which spreading may be implemented. In structural excess zones (i.e. areas where livestock production is particularly intensive), the authorized maximum annual nitrogen disposal was set at 170 kg per hectare.

In this context of rapidly evolving and increasingly

---

*Corresponding author. E-mail: stefano.farolfi@up.ac.za
Tel.: ++27 12 420 4659.

Abbreviations

CBA, Cost-Benefit Analysis; **EU,** European Union; **MAS,** Multi-Agent System; **NPV,** Net Present Value; **OM,** Organic Matter; **PV,** Present Value; **SWL,** Sow With Litters.

stringent legal requirements, stock breeders are faced with a new system of constraints and economic incentives (taxes, subsidies), which are likely to modify their approach to effluent management.

Réunion is a French overseas Department situated in the Indian Ocean, 700 Km east of Madagascar. Despite its tropical climate and hence a very different cycle of nitrogen assimilated by crops if compared to the French mainland one (higher plant productivity, different mineralisation kinetics), the island is subject to French regulations.

Livestock breeders in Grand Ilet, an area of Réunion Island characterised by a high concentration of pig farms, face the problem of dealing with large quantities of excess slurry, which they cannot fully dispose of by spreading, as they do not have sufficient arable land. Moreover, they grow mainly fresh vegetables, on which slurry spreading is prohibited.

In response to the exorbitant quantities of nitrogen provided to crops by slurry spreading in Grand Ilet (more than 1.5 T/ha per year on each cultivated plot, according to Renault and Paillat, 1999) and the environmental problems associated with this practice, two technical/organisational alternative solutions have been proposed. One consists of exporting the pig effluents outside the Grand Ilet zone to crops such as sugarcane, which require large quantities of organic matter. The other solution is to transform the liquid effluents into more manageable solid products (compost) for use on the crops of pig breeders or by other farmers and vegetables/flowers growers outside the pig production zone.

Local authorities can make use of the French and EU mentioned legislations to orient pig farmers' behaviour in the direction of a disposal of effluents complying with the new environmental regulations. Here, emphasis is placed on the combination of economic instruments (pollution charges and investment subsidies) and regulatory instruments (limits of nitrogen disposal per hectare).

This study proposes an approach that couples multi-agent simulations and cost-benefit analysis to support public decision-makers in the choice of the policy measures to implement in order to improve the local pig farms' effluents disposal.

To this purpose, the cost of different technical options available to pig farmers has been first incorporated into Echos, a multi-agent system (MAS) representing livestock effluent management in Réunion Island. Echos allows studying the impacts that potential environmental policies and investments are likely to have on pig farmers' behaviour, as well as the economic viability and management choices and the economic costs associated with environmental legal compliance as well as the subsequent diffusion of nitrogen pollution in the environment. The simulation platform utilised in this study is Cormas, multi-agent dedicated software developed at CIRAD (Bousquet et al., 1998).

A cost-benefit analysis (CBA) was then implemented on the ten year scenarios resulting from running Echos simulations that represent two different policy alternatives. The CBA allowed calculating the economic net present value of the adoption of each policy option when compared to the current situation (status quo).

A description of the MAS structure and dynamics is provided in the following section 2. Section 3 illustrates and discusses a selection of scenarios obtained through Echos and the results of the CBA conducted on these scenarios. Some concluding remarks and future developments of the research programme are proposed in section 4.

MATERIALS AND METHODS

Multi-agent systems and cost-benefit analysis

MAS in their simplest form consist of models of individuals. These individuals are often superimposed on an automated environment and are capable of observing their environment, analysing what they observe, and of modifying their behaviour accordingly (Ferber, 1999).

"Agent-based modelling takes a bottom-up approach to generating data comparable to that observable in the real system" (Deadman, 1999). This bottom-up approach consists of defining methods that correspond to the behaviour of individuals, which are part of the real world system analysed. These methods do not specify the overall behaviour of the simulations, which instead emerges as a result of the actions and interactions of the individual agents (Deadman, 1999).

Agents can be considered adaptive if they possess the following criteria:

a.) the outcome of the agent's actions within its environment can be assigned a value such as utility or fitness, and
b.) the agents change their behaviour so that they become suitable to a new situation.

Agents may possess a number of mechanisms for adjusting their actions in an effort to improve their aptitude. Complex adaptive systems usually operate far from the global optimum (Holland and Miller, 1991).

MAS therefore facilitate the "real-world" representation of actors within a system by taking into consideration the variation between individuals, and the effects of an individual's action in precipitating global patterns. MAS assist the understanding of how global patterns in societies or economies emerge from an individual's behaviour (Epstein and Axtell, 1996). The flexibility of this type of modelling tools "enables to improve both action and research outcomes through a process of iteration" involving researchers, local stakeholders and decision makers (Gummesson, 1991; Bunning, 1994; Allen, 2000). They have also been applied in economic studies of natural resource management in order to interpret possible processes of change (Balmann, 1997; Bousquet et al., 1999; Rouchier et al., 2000; Balmann et al., 2003; Ducrot et al., 2004; Farolfi et al., 2002 and 2008).

A MAS, Biomas, was developed to simulate farming practices and effluent management in Réunion Island (Guerrin et al., 1998). With the exception of transportation costs, however, Biomas neglected the costs associated with effluent management. Instead, by allocating individual annual costs to each strategy of effluent management, Echos represents possible pig farmers' reactions to the adoption of policy measures based on economic and regulatory incentives by local policy makers. Under certain hypotheses (e.g. economic rationality, cost minimisation) Echos enables the analysis of the dynamics of agents' behaviour under different policy conditions.

Table 1. Pig farmers and their characteristics in the Echos multi-agent model

Type	Number	Effluent Management	n. of Sows with litters
I	23	Do not own any spreading facility, rent spreading and transport services from other farmers.	< 16
II	30	Own spreading and transporting facilities for personal use.	16 - 42
III	3	Own spreading and transporting facilities that are also rented out to farmers of type I.	> 42

However, when moving from the individual to the collective scale, if precise economic indicators on the efficiency and effectiveness of the simulated policy options are sought, MAS analysis can be coupled with an economic approach for monetary valuation such as CBA.

According to Layard and Glaister, in any CBA exercise it is recommended that one proceeds in two stages:

a.) value the costs and benefits in each year of the project (in this case the policy option adopted); and
b.) obtain an aggregate present value of the project by discounting costs and benefits in future years to make them commensurate with present costs and benefits, and then adding them up (Layard and Glaister, 1994).

Aggregated costs and benefits deriving from different simulated policy options were then calculated for each year and a CBA over a ten-year period was implemented to obtain net present values (NPV) at year 0 for different policy options. Due to the nature of the analysis, the NPV standard formula was slightly adapted in order to calculate the present value of the cost for the implementation of a policy option (PV_c). The modified formula was:

$$PV_c = \sum_{t=0}^{n} \frac{(C_t - B_t)}{(1+r)^t} \qquad [1]$$

Where:
C_t = costs of the policy option at year t
B_t = benefits of the policy option at year t
r = discount rate
n = years of policy implementation

The multi-agent model Echos

An area of approximately 100 km^2 of Réunion was represented on a 75 by 150 automated cellular grid. Each cell represented one hectare. The grid was divided into three regions corresponding to the topography of Réunion, namely Grand Ilet (Central Island) where pig rearing takes place, the coastal zone where sugarcane is cultivated, and an intermediate non-cultivated zone.

Agents were used to represent 56 pig farmers, 6 sugarcane farmers and a public authority responsible for defining the environmental policy.

According to a direct survey conducted in Réunion Island in 2001 (Farolfi, 2003), the size of pig breeding operations varies from 1 to 50 sows with litters (SWL) per farm. Pig farmers in Echos were subdivided into three types. Each of these types manages its effluents differently, as indicated in Table 1.

Annual effluent production by pig farmers was calculated as 19.7m^3 per SWL per annum. Since effluents in Réunion contain approximately 4 kg nitrogen per m^3, this is equivalent to 78.8 kg of nitrogen per SWL per annum. Constant pig production was assumed throughout the analyses. According to Rainault and Paillat (1999), 1 m^3 = 1T of effluent [Data for model calibration came from a survey performed between 1995 and 1999 in Grand Ilet on Réunion (Cf. Reynaud, 1995 and Renault and Paillat, 1999) on a population of 56 pig breeders. This survey showed that the average farm size was 15.17 SWL, and that the average surface area of a farm was 3.76 ha, including 1.32 ha of cultivated land, 1.99 ha of fallows and 0.45 ha of buildings including gardens (Renault and Paillat, 1999].

Pig farmers were allocated farms within the Grand Ilet zone. The size of the farms was randomly selected within a pre-set range of 1 to 17 ha and was determined by the number of SWL. Pig farms consisted of a random combination of fallow (50%) and cropped (50%) cells. The cropped cells were allocated a nitrogen absorption capacity of 387.6 kg/year (weighted average of the absorption capacity of current cultivated crops) and fallow cells an absorption capacity of zero (Renault and Paillat, 1999).

Each of the sugarcane farmers was allocated a sugarcane plantation in the coastal zone. Sugarcane farm size was based on a random value between 20 and 40 ha.

Two hypothetical solutions for collective treatment of pig slurry were introduced into the model: a compost station and a wastewater treatment plant called “Bio-Armor” (Farolfi, 2003). Their location within the spatial grid was based on technical reports published by local consulting companies (Cyathea, 1999). The assumption was made that these collective treatment plants have the capacity to treat the effluent of 850 SWL (the real pig population in Grand Ilet at the moment of the survey). Echos allows running simulations where it can be chosen to activate one of the two technical solutions for collective treatment.

Legal limits for nitrogen disposal per hectare and pollution taxes per kilogram of nitrogen in excess of the legal limits were then introduced as modifiable parameters to define the environmental policy to be implemented.

A basic time step of one month was selected. In order to simulate monthly nitrogen diffusion in the environment in accordance with the topology of Réunion, it was assumed that 10% of the nitrogen present in each cell spread to lower lying cells each month. Of this, 50% spread to the eastern cells and 25% to the north-eastern and south-eastern cells respectively. At this stage of the modelling process, a nitrogen assimilation rate of 0.3% per month was allocated to all cells, irrespective of land use.

Simulation of individual effluent management by pig breeders was based on the observations of, and data collected by, Aubry et al. (2001) and Renault and Paillat (1999). An effluent storage capacity was allocated to each pig farmer.

The maximum storage capacity is reached approximately every

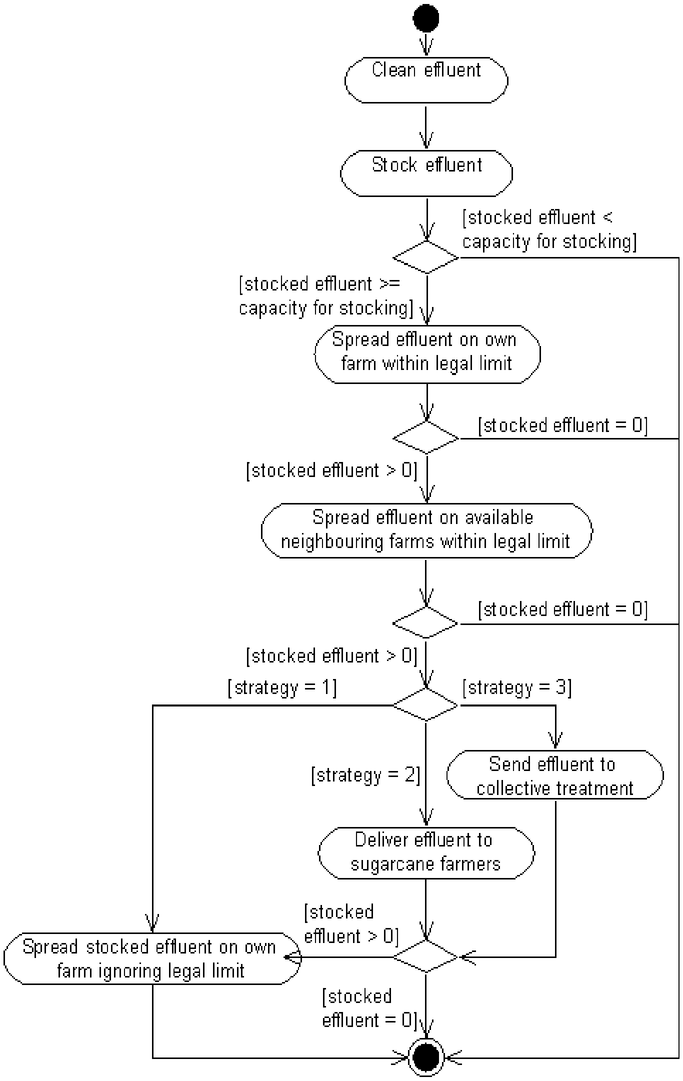

Figure 1 - Activity diagram of pig farmers' behaviour in terms of effluents management during a single time step (equivalent to one month) according to the strategy chosen

four months, upon which farmers empty their tanks and spread the effluent on their own farms in quantities compliant with environmental legislation. Effluent in excess is spread on other farms legally available for effluent disposal (i.e. where the annual quantity of effluents/ha is still below the set legal limit) within a 1 km radius (Figure 1).

Pig farmers can then dispose of the residual effluent by means of one of the following three strategies:

Strategy 1: The farmer spreads the residual slurry on his own land with no regard for environmental legislation.

Strategy 2: The farmer transports the residual slurry to the coastal sugarcane farmers, with preference for those closest to his farm. If there is no demand for effluent from sugarcane farmers, or if the effluent does not amount to a full transport load, the pig farmer spreads it on his own land. It is assumed that the only tools for effluent transport are a tractor and a trailer with a load capacity determined by the simulation parameters, with a default capacity of $10m^3$. Due to the pig farms location and the poor conditions of roads, this is the absolute maximum capacity of a transport load. The distance between the coastal zone and Grand Ilet (20 km), is used as the average distance separating pig farms and sugarcane farms.

Strategy 3: Farmer delivers the residual slurry to the collective treatment plant.

Pig farmers' generic annual cost function for slurry management can be represented as follows:

$$C_{ij} = f(CL_{ij}, ST_{ij}, SP_{ij}, TX_{ij}, TR_{ij}, CO_{ij}) \qquad [2]$$

Where:

C_{ij} = Cost for the pig farmer of type *j* adopting the strategy *i*
CL_{ij} = Cost of cleaning the stables
ST_{ij} = Cost of stocking the slurry
SP_{ij} = Spreading cost
TX_{ij} = Tax to be paid for slurry disposal above the legal limit
TR_{ij} = Cost of slurry transportation to the coastal area
CO_{ij} = Cost of collective treatment
i = Adopted strategy (1, 2, or 3)
j = Pig farmer type (I, II, or III)

The variables represented in the generic formula assume different values (positive, negative, or 0) according to the type of pig farmer and the strategy adopted.

A detailed illustration of the cost functions associated to each type of pig farmer and each adopted strategy is provided in Appendix 1.

Echos analyses all costs incurred by the various strategies throughout the simulation. At the end of each simulated year, pig farmers are given the opportunity to adopt a less expensive strategy, based on comparison of previous year costs for different strategies.

A parameter of behavioural inertia with a value between 0 and 1 was introduced. A value of 1 indicates a 100% probability that a farmer would opt for a seemingly less expensive strategy, while a value of 0 corresponds to a 0% probability that the farmer would switch strategies, even if another strategy seems economically convenient.

Sugarcane farmers spread nitrogen mineral fertilizer on their plantations according to crop requirements. The annual nitrogen requirement of 150 Kg per hectare of sugarcane used in Echos was obtained from the Union of Farming Cooperatives in Réunion (Urcoopa). Other estimates for sugarcane nitrogen requirements in Réunion range from 100 Kg/ha/year (Baldoni and Giardini, 1982) to 200 Kg/ha/year (Reynaud, 1995). In Echos, sugarcane farmers can receive pig slurry free of charge from Grand Ilet and spread it on their plantations as a substitute of the expensive mineral fertiliser. Additional mineral fertiliser can be purchased when slurry is not available in sufficient quantities.

The sugarcane farmers' annual generic cost function is represented as follows:

$$C_k = f(SP_k, ST_k, F_k) \qquad [3]$$

Where:

C_k = Cost for the sugarcane farmer adopting strategy k

Table 2. Values of Echos fixed variables

Variable	Value
Pig farmers initialised in strategy	1
Sugarcane farmers initialised in stragegy	5
Farmers change strategy during the simulation?	Yes
Likelihood of strategy change	0.5
Collective treatment	Compost
Legal limit N (Kg/ha)	170
Proportion stocking cost subsidised	0
Rate utilisation machinery	0.2
Levy charged for transport services (%TR)	0.03
Price mineral N (€/Kg)	1.52

SP_k = Cost of spreading mineral fertiliser (or slurry)

ST_k = Cost of stocking the slurry imported from the pig farms

F_k = Cost of buying mineral fertilisers

k = Adopted strategy (4 = spreading mineral fertilisers; 5 = spreading slurry; 6 = spreading both)

A detailed description of sugarcane farmers' cost functions is provided in Appendix 1.

RESULTS AND DISCUSSION

Simulating policy options

20 variables (a complete list is included in Appendix 2) can be manipulated in Echos in order to run different simulations regarding slurry management in the Grand Ilet area. Since the main objective of this paper is the evaluation of environmental policy options, only the results of simulations run by changing the following variables are shown: pollution charge at year 0; biennial increase in the pollution charge; proportion of variable transportation cost subsidised; load transportation capacity; price of compost (which, when subsidised, can reflect the level of public subsidy for a collective compost plant); and, only for some simulations, tariffs for renting out transporting facilities, as well as the size of sugarcane farms.

The other variables are fixed at the levels indicated in Table 2. The compost plant was preferred to the "Bio-Armor" facility as the collective treatment solution.

All simulations are run over a period of 10 years, and all pig farmers initially adopt strategy 1. Analysed outputs are the choice of effluent management strategy by pig farmers, the cost of effluent management for both pig farmers and sugarcane farmers, and the total nitrogen accumulated in Grand Ilet and in the coastal area.

Fixing the legal limit for slurry spreading in the pig farming area at 170 KgN/ha/year, which corresponds to the one of a structural excess zone, a number of combinations of "positive" and "negative" economic incentives taxes and subsidies respectively and their impact on the above mentioned outputs, can be explored (Table 2).

In the two policy options selected for analysis, a progressive increase of environmental taxes, combined with different levels of subsidies to cover effluent disposal costs, is simulated.

Policy option 1: Combining progressive tax and slurry transportation subsidies

Pollution charge at year 0 = 0 €; progressive pollution charge = +0.76 €/kg excess nitrogen every 2 years; proportion of variable transportation cost subsidised = 70%; load transportation capacity = 40 KgN; price of compost = 38 €/T.

In this scenario, a progressive tax is introduced and combined with a subsidy for transportation costs, whilst the compost collective plant is not subsidised. Figure 2 illustrates the dynamics of strategy choices by pig farmers within this legal context.

Starting from year 5, some pig farmers (type I) shift from strategy 1 to 3, and starting from year 7, other farmers (type II first, then also type III) shift from strategy 1 to 2. At the end of the simulation, pig farmers in strategy 2 are more numerous than those in strategy 3, but 36 farmers (15 type I, 19 type II, and 2 type III) are still in strategy 1, whilst 11 (type II and III) are in strategy 2, and 9 (8 type I and 1 type II) are in strategy 3.

A progressively increasing pollution tax forces pig farmers to modify their effluent management approach. However, at the end of the simulation, a relatively large number of pig farmers opt to keep following the status quo strategy, despite strong economic incentives (pollution charge at 3 €/kgN, and a 70% variable transport cost subsidy) to move to one of the alternatives.

Starting from year 7, sugarcane farmers receive slurry from the pig farming area and consequently their annual cost pattern is affected (Figure 3).

Expenditure on mineral nitrogen for sugarcane decreases, while spreading and stocking costs increase proportionally to the transfer of slurry from Grand Ilet to the coastal area. A limited positive effect on the accumulation of additional nitrogen in the soil is observed (from 550 T [Cumulated additional quantity of nitrogen in the soil at year 10 if all pig farmers stay in strategy 1] to 500 T at year 10) due to the combined effects of effluent transfer to the sugarcane farms and composting (Figure 4).

The problem represented by the technological and infrastructural limitations to the slurry transportation out of Grand Ilet was previously mentioned. One could then make the hypothesis that roads are improved, which allows for the transit of trucks with a loading capacity of 200 kgN = 50 T of slurry per trip. Disregarding the costs associated with road construction work, as well as the capital investment in a new truck, some scenarios introducing the improved loading capacity in the previous context were run.

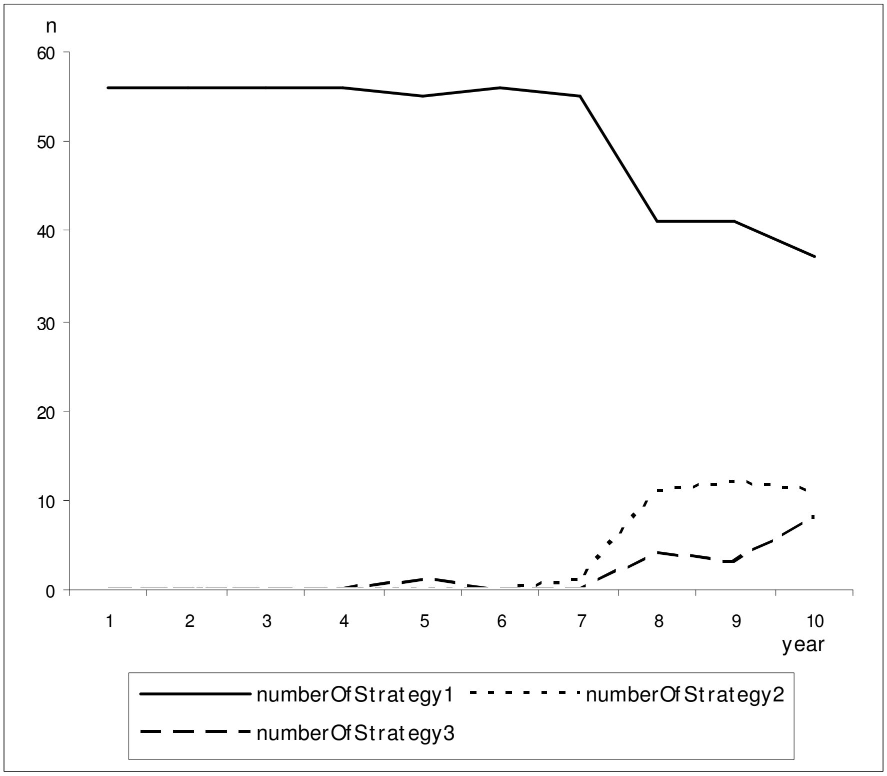

Figure 2. Policy option 1: Pig farmers' strategies

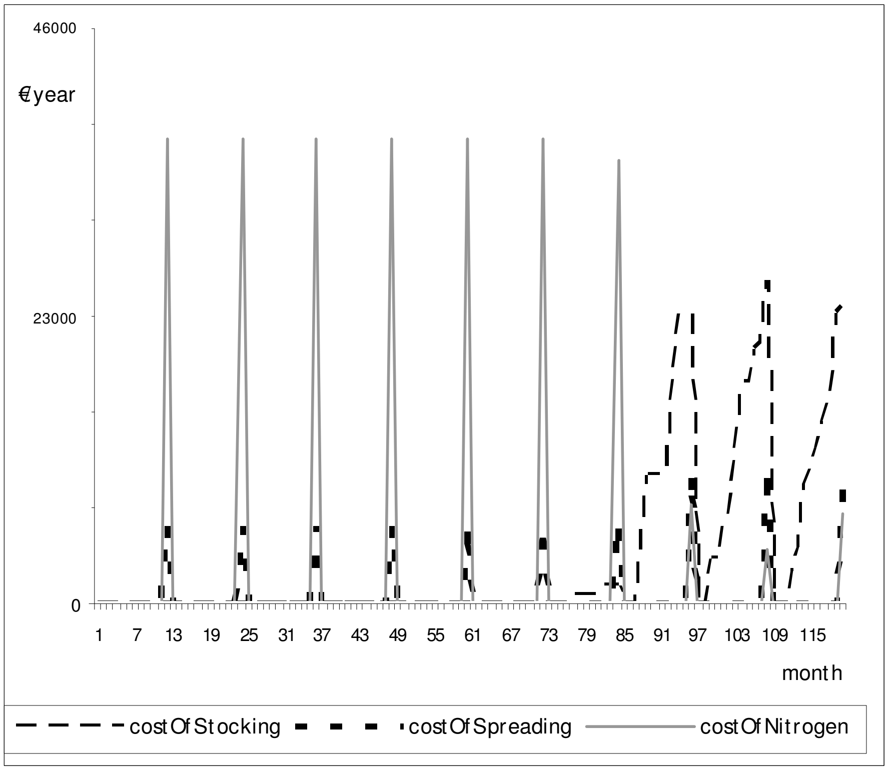

Figure 3. Policy option 1: Annual costs for sugarcane farmers

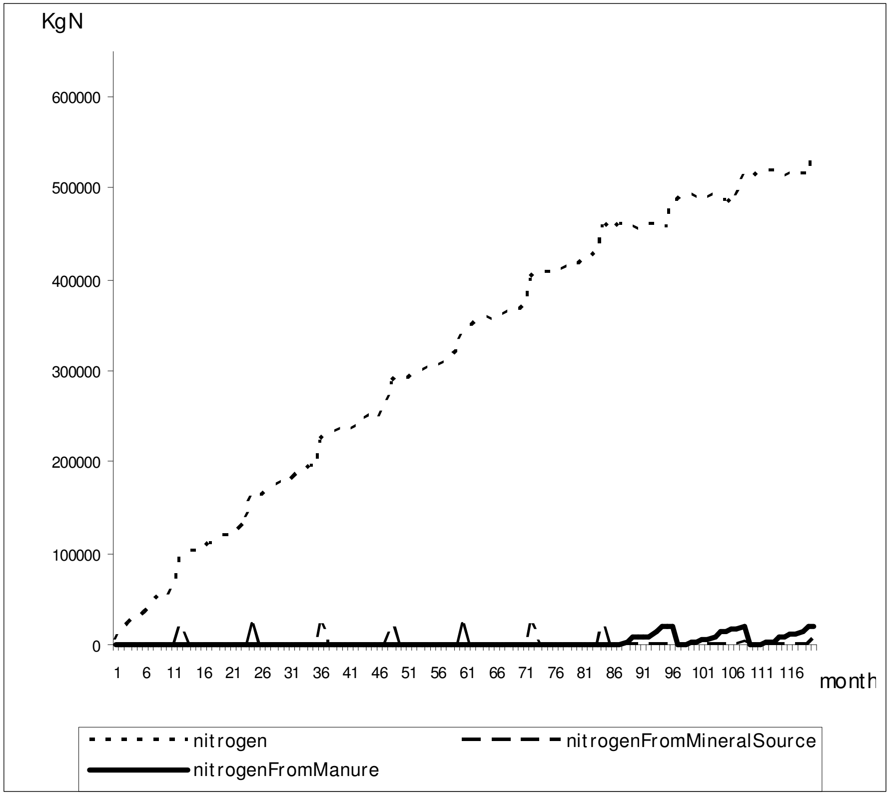

Figure 4. Policy option 1: Nitrogen dynamics

Simulations show that, *ceteris paribus*, the improved technology does not expedite sensibly the switch to strategy 2 among pig farmers. However, when doubling the tax progression (1.52 €/kg excess nitrogen every 2 years), a dramatic change in the pattern of strategy choice is observed (Figure 5).

In this case, due to the limited surface area of sugarcane farms, the demand of slurry in the coastal area is saturated at year 8. As a consequence, in the following years pig farmers willing to abandon strategy 1 are obliged to choose strategy 3.

However, simulations run doubling the available sugarcane farm surface, show that at year 10 the nitrogen demand is not saturated. At this level of pollution tax (4.58 €/KgN at year 7 and 6.10 €/KgN at year 9) an increasing number of pig farmers prefer the unsubsidised collective compost plant rather than heavily subsidised transportation to the coastal area.

Policy option 2: Combining progressive tax and subsidies for collective compost plant

Pollution charge at year 0 = 0 €; progressive pollution charge = +0.3 €/kg excess nitrogen every 2 years; proportion of variable transportation cost subsidised = 0%; load transportation capacity = 40 KgN; price of compost = 84 €/T.

A lower progressive tax (+0.3 €/kg excess nitrogen every 2 years) combined with a subsidised price for the compost produced at the collective station that includes the public subsidy will induce all pig farmers to choose strategy 3 by year 10 (Figure 6). In this option farmers choosing strategy 3 receive a public subsidy of 46 € for each T of compost. This subsidy covers 50% of the annual cost of the collective plant.

This behaviour by pig farmers would have a sensibly positive effect on the amount of additional nitrogen accumulated in the area (Figure 7).

Introducing in the simulation a public subsidy that covers 57% of the collective compost station annual cost, all pig farmers adopt strategy 3 by year two without any pollution charge.

Coupling multi-agent simulations (MAS) and cost-benefit analysis (CBA)

Annual farmer's costs and benefits calculated through simulations run with Echos were first aggregated to obtain collective values by type of farmers and for the whole

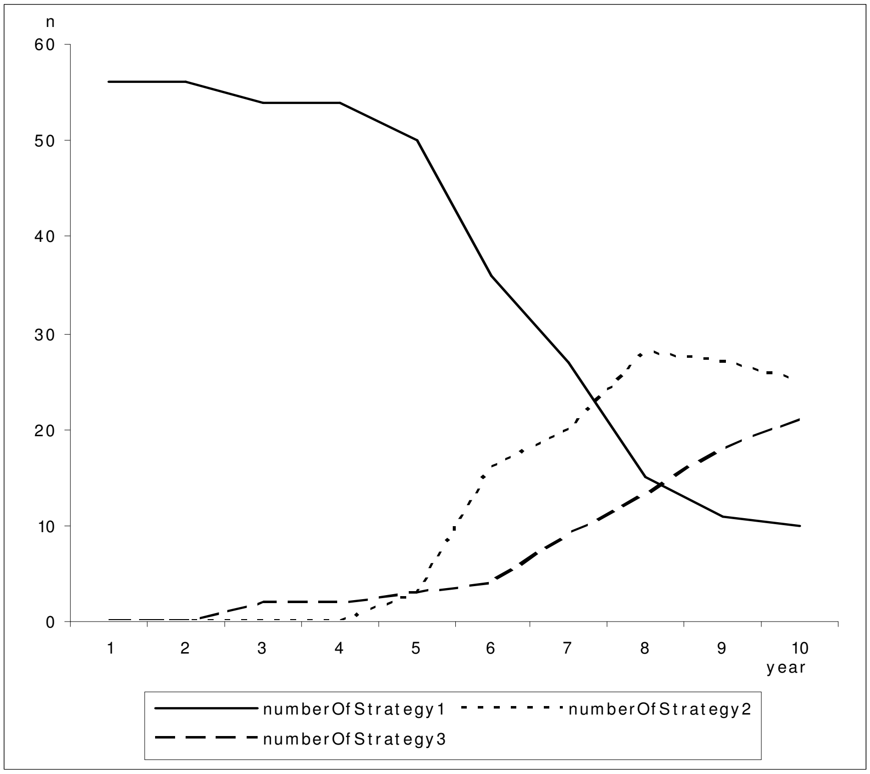

Figure 5. Policy option 1 doubling tax progression and improving roads: Pig farmers' strategies

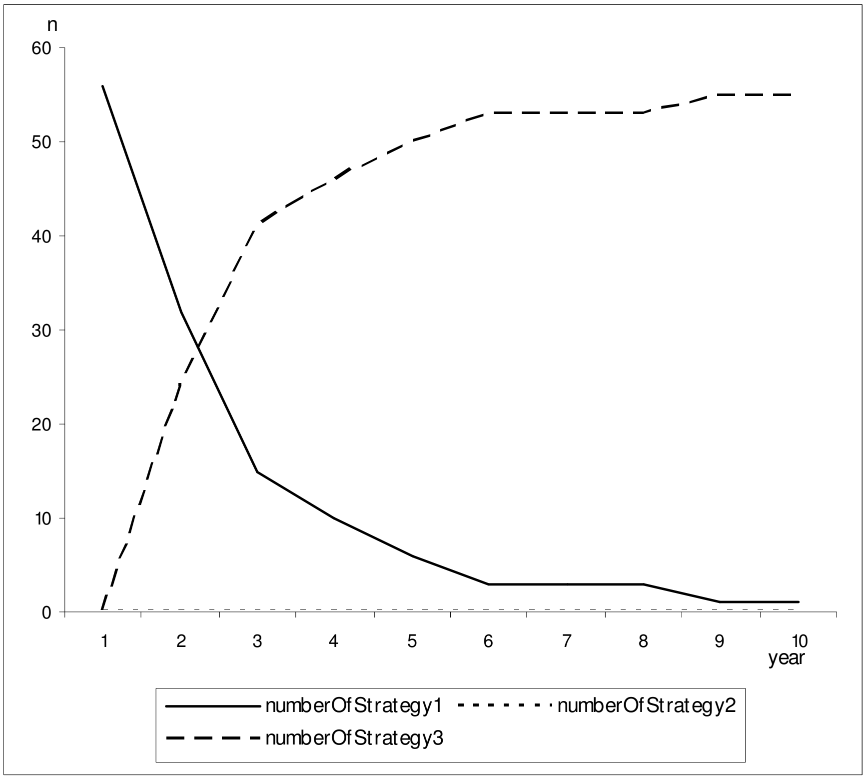

Figure 6. Policy option 2: Pig farmers' strategies

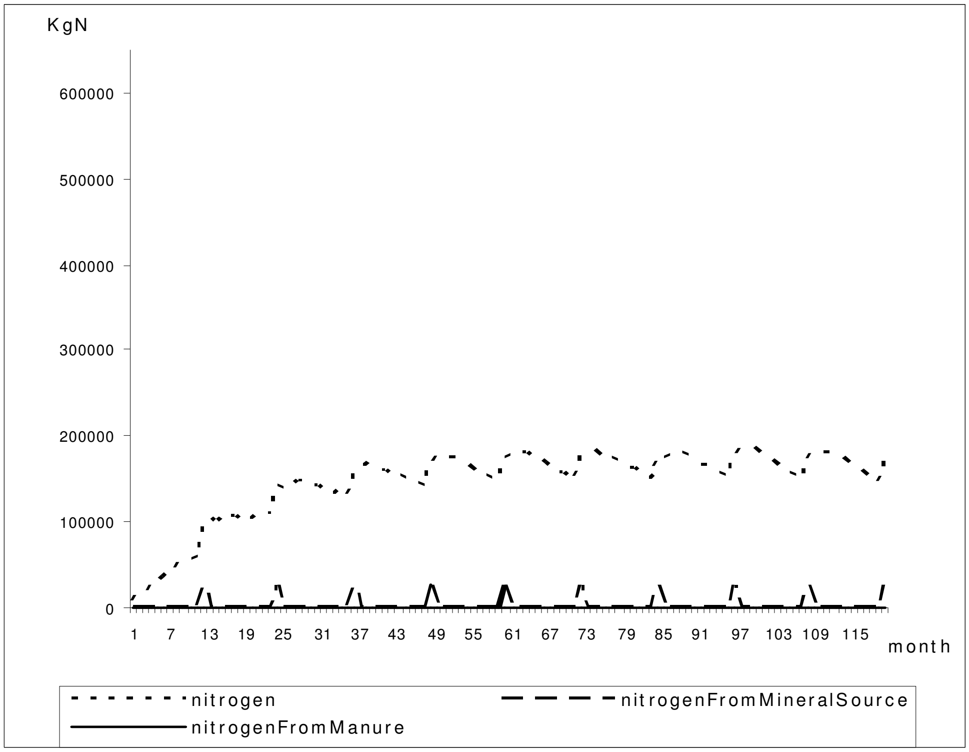

Figure 7. Policy option 2: Nitrogen dynamics

whole study area. Then the choice of a discount rate and the use of equation [1] allowed obtaining the present value of the cost (PV_c) for the simulated adoption of two different policy options. Table 3 illustrates the results of this analysis applied to the policy option consisting of a high tax (3 €/KgN) over the whole simulated period combined with a subsidy covering 70% of slurry transportation costs [In the previous section, a tax progression every 2 years was simulated. A constant level of tax in the CBA analysis simplifies calculations and reduces the number of variables changing overtime]. For this policy option, the surface of sugarcane farms in the coastal area was randomly set between 20 and 40 ha in the first scenario and between 40 and 80 ha in the second one. Costs and benefits of this option were then compared with costs and benefits of the policy option consisting of a lower tax (0.7 €/KgN) over the whole period and a subsidy covering 42% of the annual cost of a collective compost plant. No subsidy for transportation costs was contemplated in this second option.

The following incremental costs compared to the status quo were considered: incremental cost for pig farmers [resulting from the pollution taxes plus the cost of transport, or the unsubsidised cost of collective treatment, according to the policy option analysed. The reduction of spreading costs contributes to the reduction of this incremental cost] and annual subsidies to be paid by public institutions in order to cover slurry transportation or collective treatment costs.

On the other side, incremental benefits were represent- by the annual cost reduction for sugarcane farmers (re- from the use of free pig slurry instead of buying mineral fertilisers), and the double dividend for the society pro- by the tax payment for the spread of slurry above the legal limit on structural excess areas.

The reduction of accumulated additional nitrogen in the soil at year ten of the simulation was then calculated, as this represents the positive environmental impact of the adopted policy with respect to the status quo. The discounted cost of the adopted policy was then expressed in absolute terms and in terms of cost per unit of reduced pollution.

Analyses were conducted over a period of ten years, using a discount rate of 6%, a higher value than the pre-inflation rate in Réunion. This discount rate accounts for the risk of the investments (Table 3).

Results indicate that the policy option consisting of a lower tax combined with a subsidy for the collective compost plant is the less expensive. Furthermore, its impact in terms of pollution reduction is higher. Increasing the available surface in the coastal zone improves only marginally the results of the policy option aimed at transferring effluent to the sugarcane plots. In addition, the feasibility of the second policy option is far higher when compared to the previous one. In particular, the high tax imposed on pig farmers in order to push them to adopt a strategy of transfer of effluent to the coastal zone is not acceptable in the specific context, and does not

Table 3. Present values in € of the incremental cost (PV_c) of two policy options over a ten year simulation (r=6%)

Option 1. Subsidising effluent transport to sugarcane farms (20 ha > 40 ha)												
	Year	1	2	3	4	5	6	7	8	9	10	TOTAL
Subsidy		0	166, 931	226,565	226,565	226,565	226,565	226,565	226,565	226,565	226,565	1,979,450
Δ cost PF		229,618	220,550	213,130	216,031	198,321	228,855	222,748	209,008	219,695	196,336	2,154,290
Double dividend		229,618	163,969	138,473	138,931	125,191	151,145	145,038	135,878	141,985	123,206	1,493435
Δ cost PF		0	3,176	4,580	4,580	4,580	4,580	4,580	4,580	4,580	4,580	39,817
Policy option cost		0	220,336	296,641	299,084	295,115	299,695	299,695	295,115	299,695	295,115	2,600,489
Residual N (Kg)		*483,216*									**PV_c 6%**	**1,840,518**
Reduced N (Kg)		*95,047*								**PV_c /KgN reduced**		**19.36**
Option 1. Subsidising effluent transport to sugarcane farms (40 ha > 80 ha)												
	Year	1	2	3	4	5	6	7	8	9	10	TOTAL
Subsidy		0	198,779	239, 746	242,952	309,924	360,509	423,919	304,936	337,710	297,099	2,715,573
Δ cost PF		219,847	225,038	200,763	199,5452	190,076	216,489	221,832	198,015	212,366	192,061	2,076,031
Double dividend		219,847	153,282	121,374	119,389	88,244	91,145	74,198	98,321	98,626	95,725	1,160,153
Δ cost PF		0	12,258	14,406	18,940	19,460	22,437	26,391	19,047	21,032	18,482	172,453
Policy option cost		0	258,276	304,729	304,164	392,296	463,416	545,161	385,584	430,418	374,953	3,458,997
Residual N (Kg)		*403,216*									**PV_c 6%**	**2,415,103**
Reduced N (Kg)		*175,684*								**PV_c /KgN reduced**		**13.75**
Option 2. Subsidising Compost collective station												
	Year	1	2	3	5	5	6	7	8	9	10	TOTAL
Subsidy (disc.)		0	175,105	181,940	202,613	194,944	215,451	217,451	208,449	221,619	202,947	1,820,520
Δ PF Collective syst. (disc)		0	16,183	10,687	9,924	24,122	9,924	23,053	16,489	29,466	12,519	167,939
PF Tax		104,885	52,214	32,519	10,909	687	382	198	840	840	794	204,268
Double Dividend		104,885	52,214	32,519	10,909	687	382	198	840	840	794	204,268
Net costs (but subs.)		0	191,288	192,627	226,736	204,868	238,504	242,947	224,937	251,085	215,466	1,988,458
Residual N (Kg)		*135,834*									**PV_c 6%**	**1,988,458**
Reduced N (Kg)		*443,066*								**PV_c /KgN reduced**		**4.49**

Notes:
1) PF = Pig Farmers; SF = Sugarcane Farmers
2) Annual values for collective system subsidies and pig farmers' collective treatment costs are discounted in the simulation

reflect the general orientation of the environmental protection policy in France and in the EU.

Other structural and technical constraints linked to the transfer of effluent to the coastal area, namely the poor quality of the roads and the consequent low capacity load for slurry, were already mentioned. An improvement of the road connections between Grand Ilet and the coastal area would correspond to high additional costs that are not considered in this analysis. In this simulation, an optimistic load capacity for transportation of 20T of slurry was taken into account, corresponding to 80 KgN per trip. In fact, as already mentioned, the current state of the roads in the studied area allows only a load capacity of 10T of slurry.

Summarising, the results of the presented simulations show clearly that a “stick and carrot” policy based on the combined use of environmental taxes and subsidies would be effective in the studied context either through the adoption of a pollution tax higher than 0.3€/KgN, or by coupling it with a subsidy covering a significant share of the alternative strategy’s annual cost. In other terms, a low level of economic instruments does not seem to be sufficient to induce pig farmers toward a strategy of effluent management alternative to the present one, i.e. spreading all organic matter on the Grand Ilet plots.

In particular, at subsidy levels below 70% of the annual transportation cost, the transfer of effluent to the coastal area does not look attractive for the pig farmers (especially for those who do not own spreading and transport facilities).

The CBA was conducted on the two options that MAS simulations indicated to be the most applicable to the studied context showed that a lower tax on effluents coupled with a subsidized collective compost station would be economically more viable, socially more acceptable, and environmentally more effective than the option aimed at facilitating the transfer of organic matter towards the sugarcane farms of the coastal area.

CONCLUSION AND PERSPECTIVES

Pollution and environmental impacts of the agricultural sector are considered to have a growing importance in both industrialised and developing countries. Policy makers are concerned with the negative consequences on the ecological systems of intensive production activities such as livestock breeding.

To address this problem, decision-support tools able to represent the complexity of the systems at stake made of social, economic and ecological components are highly required.

MAS are powerful tools to represent complex systems and the dynamic interactions among different and spatialised agents in a specific context. Due to their features – dynamic illustration of simulations, simultaneous consideration of economic and ecological variables, spatialised representation of agents and the capacity to make them interact - MAS provide a sound basis for the creation of decision-making tools to define environmental policies at a local level. Compared to economic models based on mathematical optimisation techniques, MAS are more capable of encompassing the complexity of the economic, ecological, social and ethical relations involved in the management of environmental impacts.

However, policy makers need to challenge the status quo by reducing pollution through the selection of the policy option that guarantees the lowest possible cost to society (Baumol and Oates, 1988). To combine the accuracy of the representation of a dynamic socio-economic and environmental complex system like the presented one with the pragmatism of the actual cost calculation for the implementation of a policy option, this study proposed to couple a MAS with a CBA.

The scope of the MAS developed was to interpret the economic behaviour of pig farmers in Réunion Island subsequent to the adoption of different environmental policy options. In the multi-agent model Echos, pig farmers and sugarcane growers are numerous, and distributed over a given area with specific characteristics. Pig farmers own farms of different sizes and animal population, and have different characteristics in terms of the availability of spreading facilities.

The use of MAS enabled the consideration of multiple components, thereby creating a representation of a complex reality. More specifically, it combined both economic and ecological dynamics in a spatial model. The agents studied could adopt different strategies and evolved during a simulation. In other words, multi-agent modelling enabled the illustration of certain mechanisms that would be difficult to pinpoint using standard economic modelling methods.

The agents of Echos were assumed to be rational and well informed. However, economic players who are not entirely rational or only partly informed can also be included in MAS. These types of behaviour, not described in this paper, will be included in future project developments.

The model allowed combining the dynamics of nitrogen produced, transported and assimilated by the soil with all economic simulations. This feature of the MAS is very useful for the construction of tools for decision-making and negotiation among different stakeholders, since the environmental measures are tested not only in terms of economic efficiency and effectiveness, but also in terms of environmental sustainability.

Simulations run through Echos allowed identifying some policy options that seemed able to match the mentioned socio-economic and environmental criteria for the study area. These policy options were then tested in terms of economic costs and benefits for the society through the implementation of a CBA on the data calculated by the MAS.

Although the exercise remained at an experimental level, it showed the potential utility of combining a standard evaluation method such as CBA with MAS. In particular, the possibility to rank the different simulated scenarios through universally recognised economic criteria, such as NPV, widens significantly the field of application for MAS as decision and negotiation support tools when policy options must be chosen.

In future developments of Echos, more complex behavioural patterns, which differ from one agent to another can be introduced, since MAS provide a good means to represent agents possessing limited information and pursuing objectives other than profit maximization alone. The introduction of different strategies in a system of evolutionary games (Weibull, 1995) should allow illustrating the system's response to the introduction of technological or procedural innovations. Various forms of coordination between players will be analysed and a system of transferable pollution permits will be explored.

Finally, since a great deal of importance is attached to the ecological dynamics simulated by a model which is basically economic in nature, the methods used to represent the behaviour of nitrogen in the soil (diffusion rates that vary according to the slope and nature of the soil, different levels of soil leaching, crop assimilation capacities, etc.) will be improved.

ACKNOWLEGDEMENTS

This paper is dedicated to the memory of Louise Erasmus. Echos is based on data and information collected in 2001 through direct surveys conducted within a CIRAD research programme (ATP 99/60) co-ordinated by F. Guerrin and J. M. Paillat. Thanks to François Bousquet for his detailed and precious comments on an earlier version of this paper.

REFERENCES

Allen W (2000). The role of action research in environmental management, working paper on the website : http://nrm.massey.ac.nz/changelinks/ar_working.html.

Aubry C, Paillat JM, Guerrin F (2001). Modélisation conceptuelle de la gestion des effluents d'élevage à la Réunion. Rapport Cirad-Tera n°16/01, La Réunion, p.58.

Baldoni R, Giardini L (1982). Coltivazioni erbacee, Pàtron, Bologna, 1024 p.

Balmann A (1997). Farm-based modelling of regional structural change: a cellular automata approach. European review of agricultural economics, 24 (1): 85-108.

Balmann A, Happe K, Kellermann, K, Kleingarn A (2003). Adjustment costs of agri-environmental policy switchings. In: Janssen, M.A. (ed), Complexity and ecosystems management. The theory and practice of multi-agent systems. Edward Elgar, Cheltenham, UK, pp.127-157.

Baumol WJ, Oates WE (1988). The theory of environmental policy, Cambridge University Press, New York, Second ed. p.299.

Bousquet F, Bakam I, Proton H, Le Page C (1998). Cormas: common-pool resources and multi-agent Systems. Lecture Notes in Artificial Intelligence 1416: 826-838.

Bousquet F, Barreteau O, Le Page C, Mullon C, Weber J (1999). An environmental modelling approach: the use of multi-agent simulation. *In:* Blasco and Weill (Eds.), Advances in environmental modelling, Elsevier, pp. 113-122.

Bunning C (1994). Action research: an emerging paradigm. Brisbane: Tertiary Education Institute, The University of Queensland. [Occasional paper series - No. 4].

Cyathea (1999). Etude préalable à la mise en place d'une station de traitement collectif des effluents d'élevage porcins à Grand Ilet. Groupement des éleveurs de Grand Ilet., p.75.

Deadman PJ (1999). Modelling individual behaviour and group performance in an intelligent agent-based simulation of the tragedy of the commons, J. of Environ. Manage. 56: 159-172.

Ducrot R, Le Page C, Bommel P, and Kuper M (2004). Articulating land and water dynamics with urbanization: an attempt to model natural resources management at the urban edge, Computers, Environ. and Urban Syst. 28: 85-106.

Epstein JM, Axtell RL (1996). Growing artificial societies : Social Science from the bottom up. MIT Press, Chicago.

Farolfi S (2003). Coûts de gestion individuelle et collective d'effluents d'élevage à l'île de la Réunion, Research Report CIRAD-TERA n. 11/03, Montpellier, p.50.

Farolfi S, Le Page Ch, Tidball M, Bommel P (2002). Management of livestock effluents in Réunion – Use of a multi-agent system to analyse the economic behaviour of players, in : Urban, Ch. (Ed.) « Proceedings Workshop 2002 : Agent-Based Simulation 3 », Ghent, ISBN 3-936150-17-6, pp. 111-119 .

Farolfi S, Gumede H, Rowntree K, Jones N (2008). Local water governance in South Africa: to which extent participatory approaches facilitate multi-stakeholder negotiations? The Kat River Valley experience, Proceedings of the XIII World Water Congress, Montpellier, 1-4 September.

Ferber J (1999). Multi-agent systems. An introduction to distributed artificial intelligence, London, Addison Wesley.

Guerrin F, Courdier R, Calderoni S, Paillat JM, Soulie JC, Vally JD (1998). Biomas : un modèle multi-agents pour aider à la gestion négociée d'effluents d'élevage. *In :* Modèles et systèmes multi-agents pour la gestion de l'environnement et des territoires (N. Ferrand, Ed.), Actes du colloque, Cemagref éditions, Clermont-Ferrand (F), 5-8 octobre, pp. 359-378.

Gummesson E (1991). Qualitative methods in management research, Newbury Park, Sage.

Holland JH, Miller JH (1991). Artificial adaptive agent in economic theory. Am. Econ. Rev. 81:.365-370.

Layard R, Glaister S (eds.) (1994). Cost-Benefit analysis, Cambridge University Press, Cambridge, UK, p.497.

Renault D, Paillat JM (1999). Analyse de la production et de l'utilisation des effluents porcins à Grand-Ilet, localité de l'île de la Réunion (Cirque de Salazie). Research report Cirad-Tera, La Réunion, n°16/99, p.50

Reynaud S (1995). Diagnostic des pratiques agricoles pour une meilleure compréhension des transferts d'effluents d'élevage. Mémoire DAA Ina-PG, Paris, p.59.

Rouchier J, Bousquet F, Requier-Desjardins M, Antona M (2000). A multi-agent model for transhumance in North Cameroon. J. of Econ. Dynamics and Control, 25: 3-4, p. 527-559.

Weibull J (1995). Evolutionary game theory, Cambridge,MA, MIT Press.

APPENDIX 1: Cost functions for pig farmers and sugarcane farmers referred to the chosen strategy

The calculations contained in Farolfi (2003) and based on field surveys conducted in 2001, enabled the definition of average annual cost functions related to each strategy of slurry management in Grand Ilet (Réunion).

As for the individual management, the following basic operations have been identified: cleaning, stocking, and spreading. For each operation, average cost functions[1] were estimated according to the size of the pig farm (n. of sows with litters - SWL).

These cost functions, whose specific parameters were calculated through regressions on field data, are of the form:

$$AC = aX^{-b} \; ; \quad 0<b<1$$

Where:

AC = Average cost
X = Pig farm size (SWL)
a and b = Parameters estimated for each operation (tab. A1)

Table A1. Average cost functions' parameters for individual management operations

	Cleaning	Stocking*	Spreading (variable)	Spreading (fixed)
a	77.2	**10.1**	**46.5**	**57.8**
b	0.9	**0.4**	**0.9**	**0.7**
R^2	*0.4*	*0.9*	*0.9*	*0.9*

* for sugarcane farmers: a = 15.6; b = 0.35
Parameters in bold have significance levels > 95%

Spreading for type I = e

$$e = \begin{cases} e_1 = 1 \\ e_2 = 3 \\ e_3 = 6 \end{cases}$$

Constant values for the average cost of collective treatment, as well as for slurry transportation costs were calculated from various studies as indicated below.

A conversion rate allows using the same cost functions for both pig farmers and sugarcane farmers. If the nitrogen needs for sugarcane are considered to be 150 kgN/ha, since 1 SWL produces 78.8 kgN/year (Rainault – Paillat, 1999), 1 hectare will require the equivalent of 1.9 SWL/year.

The average cost for the pig farmer that decides to use a collective station for treating the exceeding pollution is C_{coll}. The hypothesis was made that a farmer who decides to use a collective station for treating the exceeding pollution is totally relieved of any responsibility with respect to that pollution. Therefore, the cost corresponds to a tariff that the breeder pays to the collective station's manager. This tariff, which must cover at least investment and operating costs of the collective station, is in €/kgN. Data corresponding to different types of collective stations are detailed in Farolfi (2003).

These average cost functions are crucial elements for building the annual total cost functions for each type of stockbreeder or sugarcane farmer, according to the chosen slurry management strategy.

---

[1] These functions give annual costs in €/m^3 of slurry. For the cost in €/KgN the cost should be divided by 4.

Pig farmers' annual cost functions (referring to the generic cost function [2] in the text):

As illustrated in the text, pig farmers can choose one of the three following strategies:

1) Spreading all slurry in Grand Ilet;
2) Transporting the excess slurry in the coastal area;
3) Conveying the excess slurry to a collective station for treatment (here the cases of a compost station and « Bio-Armor » facility are illustrated).

The following formulas represent the total annual cost for each type of farmer and for each strategy of slurry management.

Terms used in the formulas for cost:

C_{ij} = Annual pig farmer's total cost for the three strategies (€/year) (I = 1,2,3; j = I, II, III)

Cf_i = Component of the cost function common to the three types of pig farmers for a given strategy

z = type I farmers delivering slurry to a type III farmer; n = 23

p = Organic matter (OM) produced every year by the stockbreeder (KgN/year)[2]

Δp = Exceeding OM (KgN/year); $\Delta p = p - p^*.Sp$, where: p^* = Norm for spreading (KgN/ha), and Sp = pig farm surface

p_1 = OM transported outside Grand Ilet, where: $0<p_1<\Delta p$ (KgN/year)

τ_p = Unitary pollution charge (€/KgN); it is applied to Δp

Cl = Average cleaning cost (€/KgN)

St = Average stocking cost (€/KgN)

Sp_f = Fixed average spreading cost (€/KgN)

Sp_v = Variable average spreading cost (€/KgN)

C_{coll} = Average cost for using a collective treatment facility (€/KgN)

TC_v= Variable transport cost (€/Km/KgN)

d = Distance between Grand Ilet and the coastal zone (Km)

S = Proportion of stocking cost not subsidized, where: $0<S<1$

T = Use rate of spreading facilities, where: $0<T<1$

K = Constant cost for anti-smell products (0.2€/KgN)

e = Fixed tariff (€/m^3) paid by type I farmers to type III farmers for spreading, where: $e_1=1$; $e_2= 3$; $e_3=6$

TT = Fixed tariff for slurry transport : proportion of TC_v that type I farmer pays to type III farmer in addition to TC_v for effluents transport, where: $0<TT<1$

The formulas illustrated below are conceived to be introduced in the multi-agent model Echos. Therefore the effluent quantities that a type III pig farmer treats in addition to his effluent are represented by the quantities of p and p_1 that type I pig farmers decide deliver to type III for spreading or transporting: $(\sum_{z=0}^{n}(p_z, p_{1z}))$. According to our field surveys, this formulation corresponds to an average coefficient equal to 1.225 to be multiplied by farmer III's p.

---

[2] To calculate p, we consider that a SWL produces 19.7 tonnes/year of effluents and that the average size of a farm is 15.17 SWL. Hence, since 1 T of effluents corresponds to 4 kgN, p = 1,195.39 KgN/year for the average farm (cf. Renault and Paillat, 1999).

Spreading all in Grand Ilet (Strategy 1)

Type I

$$C_{1I} = \tau_p.\Delta p + Cl.p + (St.S + K)p + e.p$$
$$= Cf_1 + e.p$$

Type II

$$C_{1II} = Cf_1 + T.Sp_f.p + Sp_v.p$$

Type III

$$C_{1III} = Cf_1 + T.Sp_f.p + Sp_v(p + \sum_{z=0}^{n} p_z) - e\sum_{z=0}^{n}(p_z - p_{1z})$$

Transporting p_1 in the coastal area (Strategy 2), where: $0 \leq p_1 \leq \Delta p$

Type I

$$C_{2I} = \tau_p(\Delta p - p_1) + Cl.p + (St.S + K)p + e(p - p_1) + TC_v.d.p_1(1 + TT)$$
$$= Cf_2 + e(p - p_1) + TC_v.d.p_1(1 + TT)$$

Type II

$$C_{2II} = Cf_2 + T.Sp_f.p + Sp_v(p - p_1) + TC_v.d.p_1$$

Type III

$$C_{2III} = Cf_2 + T.Sp_f.p + Sp_v[(p - p_1) + \sum_{z=0}^{n}(p_z - p_{1z})] - e\sum_{z=0}^{n}(p_z - p_{1z}) + TC_v.d(p_1 + \sum_{z=0}^{n} p_{1z})$$
$$-(TC_v.d\sum_{z=0}^{n} p_{1z})(1 + TT)$$

Using a collective system facility for treating the exceeding pollution (Strategy 3): $p_1 = \Delta p$

Type I

$$C_{3I} = Cl.p + (St.S + K)p + e(p - p_1) + C_{Coll}\,p_1$$
$$= Cf_3 + e(p - p_1) + C_{Coll}\,p_1$$

Type II

$$C_{3II} = Cf_3 + T.Sp_f.p + Sp_v(p - p_1) + C_{Coll}\,p_1$$

Type III

$$C_{3III} = Cf_3 + T.Sp_f.p + Sp_v[(p - p_1) + \sum_{z=0}^{n}(p_z - p_{1z})] - e\sum_{z=0}^{n}(p_z - p_{1z}) + C_{Coll}\,p_1$$

Sugarcane farmers' annual cost functions (referring to the generic cost function [3] in the text):

The following terms have been added to those employed in the previous formulas:

α = Sugarcane needs in nitrogen (Kg/ha/year ; here $\alpha = 150$)

S_s = Surface cultivated with sugarcane by the farmer (ha ; here $20<S_s<40$)

St_{sug} = Average stocking cost for sugarcane farmer (€/KgN)[3]

$Sp_{v\,min}$ = Variable average spreading cost for mineral fertilizers[4]

f = Price of mineral fertilizers (€/KgN ; here f = 1.5)

The following formulas represent the annual total cost related to nitrogen fertilising for the sugarcane farmers in the coastal area. 3 strategies are illustrated.

Spreading mineral fertilizers[5]

$$C_4 = \alpha . S_s (T.Sp_f + Sp_{v\min} + f + St_{sug})$$

Spreading slurry from pig breeders

$$C_5 = \alpha . S_s (T.Sp_f + Sp_v + St_{sug} .S + K)$$

Spreading both[6]

$$C_6 = T.Sp_f .\alpha . S_s + (Sp_{v\min} + f)(\alpha . S_s - p_1) + Sp_v . p_1 + (St_{sug} .S.\alpha . S_s) + K.p_1$$

---

[3] This average cost differs from the one calculated for pig breeders. In fact the stocking tanks required here are larger, and therefore the cost functions cannot be the same as in Grand Ilet.

[4] This cost (cf. Farolfi et al, 2002) is considered to be independed of the spreaded quantity of fertilizer (0.1 €/KgN). Due to the far higher nitrogen concentration in mineral fertilizers, this cost is much lower than the one we obtain through the function Sp_v.

[5] The last term of the function will exist only if the farmer decides at least once to spread slurry during the simulation. He has therefore invested in stocking facilities. If he comes back to mineral fertilizers, he will continue to pay fixed stocking costs for the whole simulation.

[6] This strategy is not considered in the present version of Echos.

APPENDIX 2

Table A2. Simulation variables in Echos

Name	Values
Pig farmers initialised in strategy	1; 2; or 3
Sugarcane farmers initialised in stragegy	4 or 5
Do the farmers change strategy during the simulation?	Yes or No
Likelihood change stragegy 1	0 to 1
Likelihood change stragegy 2	0 to 1
Likelihood change stragegy 3	0 to 1
Collective treatment	Compost or Bio-Armor
Legal limit N (KgN/ha)	0 to 1000
Initial tax pollution (€/kgN)	0 to 15
Tax pollution Increase every 2 years (€/kgN)	0 to 3
Proportion variable TC subsidised	0 to 1
Proportion stocking cost subsidised	0 to 1
Rate utilisation machinery	0 to 1
Capacity transport N (kgN)	0 to 200
Levy charged for transport services (%TR)	0 to 1
Price mineral N (€/KgN)	0 to 4.5
Minimum size of a sugarcane farm (ha)	20 to 40
Maximum size of a sugarcane farm (ha)	40 to 80
Price of compost (€/T)	0 to 89
Price for renting out spreading facilities (€/KgN)	0.25; 0.75; or 1.52